LOOKING FOR METHANOL: IDENTIFYING THE EXPANSE OF THE GALACTIC HABITABLE ZONE

By

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Abstract:

Defining the expanse of the Galactic Habitable Zone (GHZ) has long been a major debate in astrobiology. The GHZ is known as the region within a galaxy where life is most likely to develop. Older definitions propose the GHZ spans a radial distance of about 9 kpc from the galactic center based on conditions such as metallicity and supernovae discharge. A recent survey of formaldehyde suggested the GHZ extends as far as 25 kpc from the galactic center based on distributions of prebiotic molecules. In order to further investigate and constrain the extent of the GHZ, we surveyed methanol molecules in 17 molecular clouds in outer regions of our galaxy. This initial survey consisted of clouds located between 13.2 and 22.6 kpc away from the galactic center. Methanol (CH3OH) is the starting ground of many prebiotic species such as sugars, amino acids, and other important biomolecules. We detected methanol in 82% of our surveyed molecular clouds, including 5 clouds with R_G >18 kpc (detection rate 100%). Establishing the quantity of methanol dispersal in far regions of the Milky Way allows us to get one step closer to defining the region in our galaxy where life has the possibility to arise.

Expanding the Edge: Where does the Galactic Habitable Zone End?

The idea of a Galactic Habitable Zone (GHZ) has evolved over the years from being a concept limited to the region of the galaxy deemed suitable for the formation intelligent life (Marochink and Mukhin (1986)), to “the region in the Milky Way where an Earth-like planet can retain liquid water on its surface and provide a long-term habitat for animal-like aerobic life.” (Gonzalez *et al*. (2001)). This shift from focusing solely on where intelligent life could survive to including simplistic life allowed for an extension of the idea of a GHZ to describe portions of the Milky Way where conditions aren’t inhospitable for the development of life in general. Later, the idea was updated so that a number of physical characteristics such as metallicity, supernovae frequency, and distance from the galactic center might either benefit or hinder the development of life. Recently, in a study completed in 2004 (Lineweaver *et al.* (2004)) the aforementioned ideas were combined in consideration with a timescale to further define conditions for the development of life. Their end conclusions were that the GHZ stretches to form an annulus anywhere from 7-9 kpc in distance from the Galactic Center and it continues to widen as time continues.

In 2008, Samantha Blair (Blair *et al*. (2008)) studied the distribution of formaldehyde in molecular clouds in the outer regions of the Milky Way. Formaldehyde (H2CO), is a key factor in the creation of the amino acid glycine in conjunction with ammonia (NH3) and Hydrogen Cyanide (HCN). Studying the extent of the formaldehyde distribution in the galaxy was interpreted as a method to help constrain the borders of the GHZ. The study found that formaldehyde was present in clouds over 25 kpc away from the Galactic center, a distance that they then proposed should be the new standard for the GHZ. This 25 kpc proposal nearly tripled the distance Lineweaver calculated in 2004. This wide annulus presented an additional consideration to the current idea of a GHZ: the presence and abundance of prebiotic molecules and their precursors. Thinking about the basic molecules that lead to the standard monomers of life such as amino acids and sugars allows us to look for an outer "edge" and constrain the boundaries of the Galactic Habitable Zone.

Methanol is the simplest alcohol that has been discovered in the interstellar medium (ISM). It has the property of not only being an important precursor to molecules such as methyl formate (HCOOCH3), acetaldehyde (CH3CHO), glycolaldehyde (HOCH2CHO), and dimethyl ether (CH3OCH3); but also happens to be the starting ground of many prebiotic species such as simple sugars and amino acids. (Boyer *et al.* (2016)). With this information, we hypothesized that locating methanol in the outer reaches of the galaxy will strengthen the argument that the galactic habitable zone is indeed larger than previously thought ten years ago.

Methanol: A Prebiotic Powerhouse

How life got its start has long been question left unanswered. In the early 1920s, A.I. Oparin and John Haldane independently published their theories on life's genesis. The Oparin-Haldane theory is now referred to as the chemical evolution hypothesis. This theory suggests that life on earth arose only after the evolution of organic materials. Unfortunately, testing this hypothesis was deemed too difficult during this time (Kobayashi *et al.* (2017)). However, by the mid 20th century, Stanley Miller and Harold Urey reported the first successful abiotic synthesis of amino acids via electrical discharges in a mixture of methane (CH_4), ammonia (NH_3), water (H_2O), and hydrogen (H_2) gases. This groundbreaking experiment effectively proved that the chemical evolution hypothesis could be tested.

By the late 20th century several experiments had been conducted to simulate the life-bringing early-earth atmosphere. In the majority of these studies, the gaseous forms of methane and ammonia acted as reducers amongst energy sources such as spark discharges, ionizing radiation, and thermal energy. In the end, there were several reports of success in the synthesis of aldehydes, amino acids, and other organic compounds. Notably, the compounds methyl formate (HCOOCH_3), the simplest form of an aster, and dimethyl ether (CH_3OCH_3), the simplest ether were formed from reactions with methanol gas.

Methanol is not only believed to be an integral precursor to the molecules methyl formate and dimethyl ether, but also to many prebiotic species such as simple sugars, nucleic acids, and amino acids like glutamic acid (Ackermann and Babel (1994)) and methionine (Dekker et al. (1949)). Simplistic monosaccharide sugars fall under the biological molecule category of carbohydrates. These compounds of carbon and water follow the chemical formula:

$$(C + H_2O)_n = C_nH_{2n}O_n$$

Where n ≥ 2 is the number of carbon or oxygen atoms present. A two-carbon sugar is a diose, a three-carbon sugar is a triose, and so on. Glycolaldehyde (alternatively called diose) is the simplest possible sugar, consisting of a two-carbon monosaccharide ($C_2H_4O_2$) (Hollis, Lovas, and Jewell (2000)), and is found to be formed as a product of UV-irradiation of methanol ices. This same process leads to the formation of the triose monosaccharide, glyceraldehyde ($C_3H_6O_3$), as well.

Monosaccharide sugars, being carbohydrates, are constituents of nucleic acids DNA and RNA. The pentose sugar D-ribofuranose is the sugar subunit in RNA, which is thought to be the original genetic material DNA evolved from in the primordial RNA world state (Marcellus *et al.* (2015)). However, the exact origins of the ribose sugar necessary for the formation of RNA still remain unknown. Recently, an experiment showed that the origins of ribonucleotides could have arose from glycolaldehyde and glyceraldehyde starting materials via pentose amino-oxazolines (Powner, Gerland, and Sutherland (2009)). Powner's data supports the idea that the simple molecule of methanol contributes to a wide variety of complex organic molecules, including important molecular stepping stones such as sugars and nucleic acids related to the origins of life.

Where did this precursory molecule of methanol come from? Miller and other scientists of the 20th century demonstrated that a reducing atmosphere (H_2 and CH_4 rich) coupled with energy discharges could give rise to the formation of complex organic molecules such as methanol on early earth. However, the exact composition of primordial earth's atmosphere is unknown, and many current views assert that the atmospheric conditions were either neutral or oxidizing-consisting predominantly of water, carbon dioxide (CO_2), and nitrogen (N_2) gases with trace amount of H_2 and CH_4. Discharge experiments under these oxidizing conditions don't readily produce organic molecules such as methanol. However, there is a possibility that the production/delivery of prebiotic molecules came from extraterrestrial sources. For example, cometary ices are predominately water, and contain many small molecules important to prebiotic chemistry such as carbon dioxide, ammonia, and methanol (Goldman *et al.* (2010)). The flux of organic molecules delivered from comets and asteroids during bombardment periods in early earth may have been as high as 1×10^{13} kilograms per year (Blank *et al.* (2001)), delivering a sufficient amount of methanol to early earth for future reactions. This direct introduction of methanol molecules to a planet's surface via impacting comets or asteroids would benefit most from a normal to high abundance of CH_3OH present in the parent molecular cloud, because comets and asteroids formed in the protoplanetary disk directly reflect a cloud's chemical composition (Blair *et al.* (2008)).

Remote Molecular Clouds: Distant Centers for Possible Future Life

Methanol, being the simplest alcohol discovered in the ISM, can be detected in both ambient and star-forming regions of interstellar clouds (Herbst (1991)). In our galaxy, nearly all known regions of star formation happen within molecular clouds. The correlation between giant molecular clouds (GMCs) and other phases of the ISM differs by GMCs maintaining an internal pressure roughly an order of magnitude higher than that of other phases within the ISM (Scoville and Sanders (1987)). Although GMCs are not in equilibrium with the more diffuse phases of the ISM, the young stars that form within them ultimately become massive stars and supernovae, effectively seeding the rest of the ISM with their contents.

The end stages of a supernova explosion culminate in a remnant shell of gas and dust discharged from the explosion center. This remnant is enriched with relatively light elements such as helium and carbon, as well as heaver elements such as silicon, nickel and iron, which are elements critical for rocky planet formation (Close (2013)). Along with elements, the remnant shell will also contain molecules that were present within the star's parent molecular cloud. If prebiotic molecules are present in the parent molecular cloud, the resulting supernovae could eventually give rise to the emergence of life. Thus, we may begin to determine how favorable outer regions of the galaxy are for the formation of life by surveying molecular clouds for the presence of methanol.

Observations and Sample Selections:

It is likely that methanol shares a similar distribution to that of carbon monoxide, the second most abundant molecule and sufficient ground-based tracer of molecular gases within the ISM. To investigate the scope of CH_3OH molecules in far regions of the galaxy, we conducted a survey of 17 molecular clouds taken from three catalogues.

1. The Wouterloot and Brand (1989) catalogue of IRAS sources beyond R_o. These IRAS sources are primarily located in the second and third galactic quadrants where infrared colors typical of star-forming regions have been detected. These sources also have the distinction of both CO emissions being detected therein.
2. The Bronfman, Nyman, and May (1996) CS_{2-1} emission catalogue. This catalogue surveyed CS_{2-1} emissions toward IRAS point sources along the galactic plane. It differs from our first source by including a representation of the first galactic quadrant and by its nature, the CS_{2-1} line traces a denser molecular gas than the CO_{1-0} line.
3. The Blair, Magnani, Brand, and Wouterloot (2008) $H_2CO_{2_{12}-1_{11}}$catalogue. This catalogue examined the expanse of $H_2CO_{2_{12}-1_{11}}$ emissions in the first, second, and third galactic quadrants and provided a framework for detecting a more complicated molecular gas than either CO or CS.

From these three catalogues, we then selected source candidates based on their reported signal strength (the higher the value, the more favored the source was to initially look into), their distance from the galactic center, and their relative sidereal times. In the end, 17 strong molecular cloud sources were selected, all located at distances between 13.2 and 22.6 kpc away from the galactic center. A histogram plotting the distributions of surveyed clouds and detections within is present in Figure 1, and the assumed kinematic positions of all sources are listed in

Table 1. Each object was observed at a wavelength of 96.7 GHz at the Arizona Radio Observatory 12-meter telescope at Kitt Peak, Arizona between the months of October 2018 and January 2019.

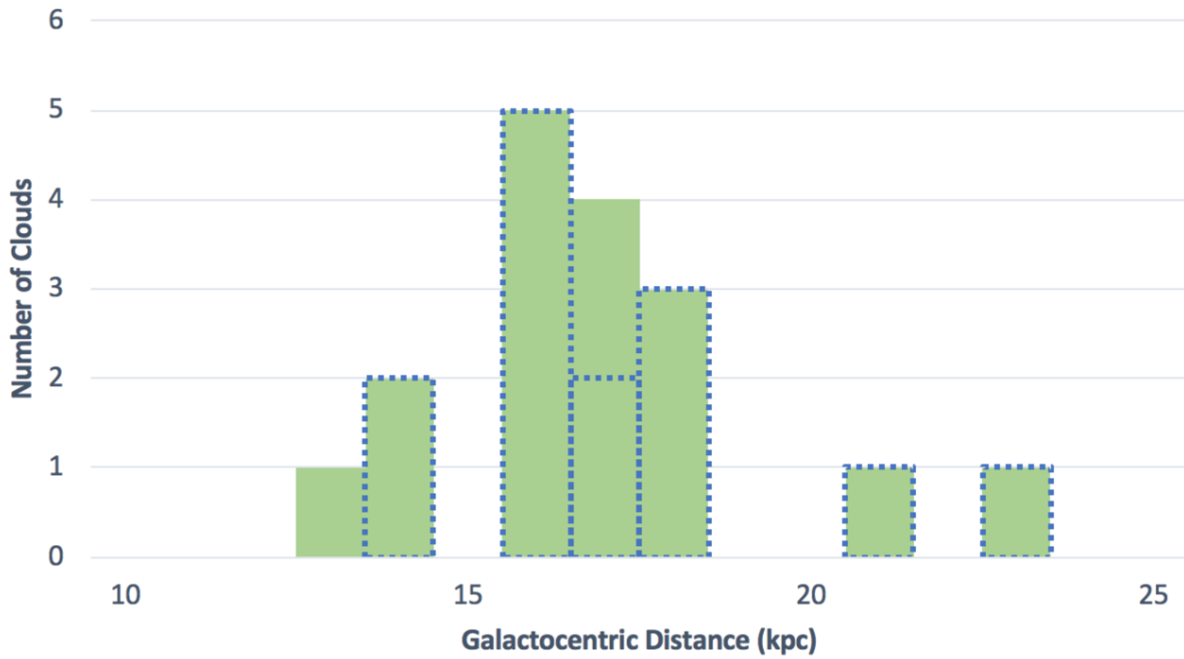

Figure 1: Histogram of the galactocentric distribution of observed clouds. The distance of the clouds is denoted by units of kpc away from the Galactic Center. The total number of clouds (17) is represented by the solid green bars and the clouds with detections (14) by the blue dashed bars.

All observations made at the 12-meter telescope were done in position-switching mode in order to maximize the velocity coverage. We oscillated with an off position 1° to the east or west of the source in azimuth. Methanol line antenna temperatures are corrected for spillover and scattering efficiency at the 12-meter telescope. This results in T_R^*, the uncorrected radiation temperature from the antenna-source coupling efficiency, η_c. The 12-meter telescope at 96.7 GHz has a η_c equal to about 0.85.

Table 1: $CH_3OH - A$ *Observations in Cold Molecular Clouds at 96.7 GHz*

Source	*l* (*degrees*)	*b* (*degrees*)	R_G (*kpc*)	T_R^* (*K*)	*ΔV* ($km \cdot s^{-1}$)	*rms* (*mK*)
WB89-060	95.054	3.972	14.0	0.112	2.40	7.00
WB89-076	95.248	2.405	15.7	0.034	1.92	3.50
WB89-380	124.643	2.539	17.0	0.024	3.36	4.30
WB89-391	125.805	3.047	16.9	0.031	1.44	2.80
WB89-399	128.776	2.012	16.8	-----	-----	-----
WB89-437	135.278	2.798	16.2	0.038	2.88	4.30
WB89-501	145.197	2.988	16.4	0.018	1.92	5.70
WB89-621	168.063	0.820	22.6	0.100	1.92	3.30
WB89-640	167.060	3.464	18.4	0.080	2.88	2.70
WB89-670	173.014	2.377	18.4	0.071	1.44	3.00
WB89-705	174.734	3.725	21.4	0.093	0.96	4.10
WB89-793	195.822	-0.568	18.1	0.071	1.44	2.40
WB89-847	209.080	-1.949	16.5	-----	-----	-----
WB89-898	217.604	-2.618	16.4	0.027	2.40	4.40
WB89-910	212.187	1.309	15.9	0.040	1.92	5.20
19383+2711	62.575	2.387	13.2	-----	-----	-----
19423+2541	61.719	0.864	13.6	0.032	2.40	5.60

Table 2: CH_3OH Observations in Cold Molecular Clouds. This table lists all sources examined in this survey project. Column one lists source name. Column two and three list the galactic latitude and longitude. Column four gives the source's galactocentric distance. Columns five, six, and seven list the uncorrected radiation temperature, line width (Full-width at Half Maximum), and *rms* noise levels for each source.

Results:

We searched for methanol using a frequency of 96.7 GHz on 17 distant molecular clouds. Out of this group of 17, methanol emissions were detected in 14 clouds, generating an overall detection rate of 82%. Far-molecular clouds are defined as those with R_G > 16 kpc. Of the 9 clouds in our survey with R_G > 16 kpc, we detected methanol emissions in 7, producing a detection rate of 77%, which is almost equal to the detection percentage of the entire survey. Surprisingly, of the clouds observed at 96.7 GHz and R_G > 18, there was a methanol detection rate of 100%. These findings indicate that methanol may be an abundant molecule in the outer regions of our galaxy. The 96.7 GHz spectrum for our farthest source, WB89-621, at R_G = 22.6 is shown in Figure 2a. Five other sources with detections in descending order of R_G are shown in figure 2b-2f.

The distance, R_G, represents the kinematic distance of the source, which is given by the equation,

$$R_G = \Theta\, R_o \frac{v_{LSR}}{\sin(l)\cdot\cos(b)} + \Theta_o{}^{-1} \text{ kpc}$$

In this equation, l and b represent the galactic latitude and longitude of the source, R_o is held constant at 8.5 kpc, the circular rotation velocity at the position of the sun is represented by Θ_o, and is 220 $km \cdot s^{-1}$, and Θ represents the circular rotation velocity of the object in question. Kinematic distances can sometimes cause ambiguity when observing clouds in the inner galaxy due to the fact that the radial velocity of a cloud with respect to its orbital velocity around the galactic center is the same at near and far distances (Roman-Duval et al. (2009)). This ambiguity is less prominent in the outer galaxy, and so R_G was a sufficient measurement to be used to gauge distances of far molecular clouds.

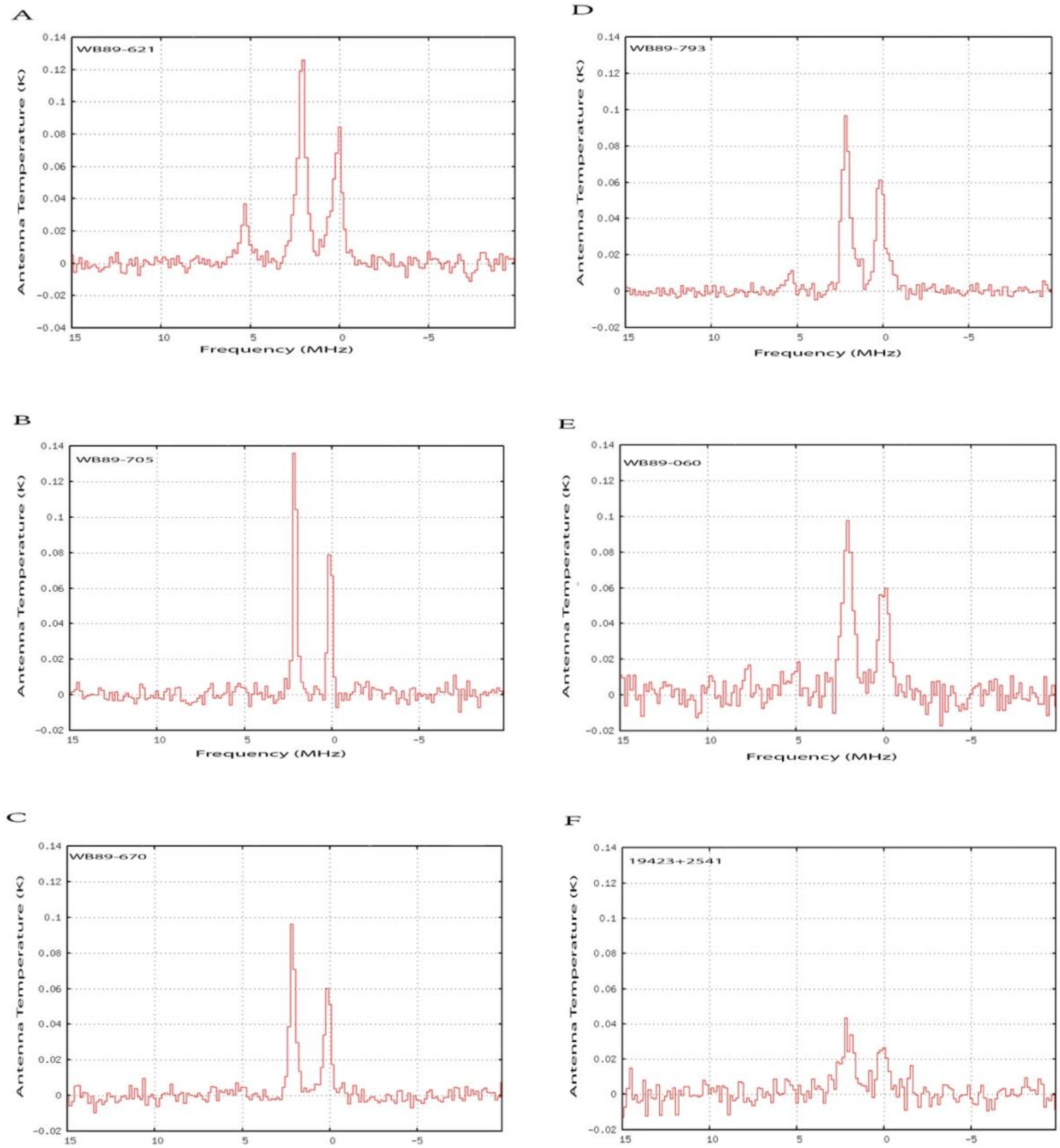

Figure 2: CH_3OH spectrums observed at 96.7 GHz. (A) CH_3OH spectrum at 96.7 GHz for giant molecular cloud WB89-621. This cloud is 22.6 kpc away from the galactic center and was our most distant source observed. (B) CH_3OH spectrum at 96.7 GHz for cloud WB89-705. This cloud has a location of R_G 21.4 kpc. (C) CH_3OH spectrum at 96.7 GHz for cloud WB89-670. This cloud has a location of R_G 18.4 kpc. (D) CH_3OH spectrum at 96.7 GHz for cloud WB89-793. This cloud has a location of R_G 18.1 kpc. (E) CH_3OH spectrum at 96.7 GHz for cloud WB89-060. This cloud has a location of R_G 14.0 kpc. (F) CH_3OH spectrum at 96.7 GHz for cloud 19423+2541. This cloud has a location of R_G 13.6 kpc.

Table 2: $CH_3OH - A$ *Column Densities in Cold Molecular Clouds at 96.741 GHz*

Source	ΔV ($km \cdot s^{-1}$)	T_{ex} (K)	T_R (K)	H_2 *Density* (cm^{-3})	$N(CH_3OH - A)$ (cm^{-2})	*abundance*	tau
WB89-060	2.40	15	$1.117 \cdot 10^{-1}$	$1.1 \cdot 10^{6}$	$0.741 \cdot 10^{13}$	$7.97 \cdot 10^{-10}$	$1.015 \cdot 10^{-2}$
WB89-076	1.92	10	$6.940 \cdot 10^{-2}$	$1.0 \cdot 10^{5}$	$3.015 \cdot 10^{12}$	$6.03 \cdot 10^{-10}$	$1.297 \cdot 10^{-2}$
WB89-380	3.36	10	$3.180 \cdot 10^{-2}$	$1.0 \cdot 10^{5}$	$2.754 \cdot 10^{12}$	$2.42 \cdot 10^{-10}$	$5.927 \cdot 10^{-3}$
WB89-391	1.44	15	$4.334 \cdot 10^{-2}$	$1.4 \cdot 10^{6}$	$1.180 \cdot 10^{12}$	$2.27 \cdot 10^{-10}$	$3.916 \cdot 10^{-3}$
WB89-437	2.88	15	$6.471 \cdot 10^{-2}$	$3.3 \cdot 10^{6}$	$0.600 \cdot 10^{13}$	$4.23 \cdot 10^{-10}$	$5.772 \cdot 10^{-3}$
WB89-501	1.92	10	$4.002 \cdot 10^{-2}$	$1.0 \cdot 10^{5}$	$0.867 \cdot 10^{12}$	$7.74 \cdot 10^{-11}$	$7.462 \cdot 10^{-3}$
WB89-621	1.92	15	$1.471 \cdot 10^{-1}$	$3.6 \cdot 10^{6}$	$0.927 \cdot 10^{13}$	$7.13 \cdot 10^{-10}$	$1.314 \cdot 10^{-2}$
WB89-640	2.88	15	$1.059 \cdot 10^{-1}$	$3.2 \cdot 10^{5}$	$0.741 \cdot 10^{13}$	$2.32 \cdot 10^{-9}$	$9.709 \cdot 10^{-3}$
WB89-670	1.44	10	$1.153 \cdot 10^{-1}$	$5.5 \cdot 10^{5}$	$0.266 \cdot 10^{13}$	$3.64 \cdot 10^{-10}$	$1.830 \cdot 10^{-2}$
WB89-705	0.96	10	$1.623 \cdot 10^{-1}$	$1.0 \cdot 10^{5}$	$0.711 \cdot 10^{13}$	$4.18 \cdot 10^{-9}$	$3.050 \cdot 10^{-2}$
WB89-793	1.44	15	$1.177 \cdot 10^{-1}$	$4.5 \cdot 10^{5}$	$0.426 \cdot 10^{13}$	$7.22 \cdot 10^{-10}$	$1.075 \cdot 10^{-2}$
WB89-898	2.40	10	$3.353 \cdot 10^{-2}$	$1.0 \cdot 10^{5}$	$2.293 \cdot 10^{12}$	$9.17 \cdot 10^{-10}$	$6.579 \cdot 10^{-3}$
WB89-910	1.92	15	$4.933 \cdot 10^{-2}$	$6.6 \cdot 10^{6}$	$0.341 \cdot 10^{13}$	$1.03 \cdot 10^{-9}$	$4.334 \cdot 10^{-3}$

Table 2: ***CH_3OH-A Column Densities in Cold Molecular Clouds calculated via RADEX.*** *Excitation condition held constant: background temperature = 2.73 K.* This table lists column densities of 2_0 – 1_0 methanol in the examined sources of this survey project. Column one lists source name. Column two gives the source's line width (Full-width at Half Maximum). Column three lists the kinetic temperature of the medium. Column four gives the radiation temperature. Column five gives the number density of collision partners. Column six gives the column density of each source to calculate the line strengths of methanol within each molecular cloud. Column seven provides the fractional abundances for each source. Column eight lists the tau of each source, which represents the optical depth at the center of the spectral line.

Table 3: $CH_3OH - E$ *Column Densities in Cold Molecular Clouds at 96.739 GHz*

Source	ΔV *(km· s^{-1})*	T_{ex} *(K)*	T_R *(K)*	H_2 *Density* *(cm^{-3})*	*N($CH_3OH - E$)* *(cm^{-2})*	*abundance*	tau
WB89-060	2.40	15	$7.057 \cdot 10^{-2}$	$1.1 \cdot 10^{6}$	$0.722 \cdot 10^{13}$	$7.76 \cdot 10^{-10}$	$6.383 \cdot 10^{-3}$
WB89-076	1.92	10	$3.411 \cdot 10^{-2}$	$1.0 \cdot 10^{5}$	$0.185 \cdot 10^{13}$	$3.70 \cdot 10^{-10}$	$7.023 \cdot 10^{-3}$
WB89-380	3.36	10	$2.352 \cdot 10^{-2}$	$1.0 \cdot 10^{5}$	$0.223 \cdot 10^{13}$	$1.96 \cdot 10^{-10}$	$4.839 \cdot 10^{-3}$
WB89-391	1.44	15	$3.059 \cdot 10^{-2}$	$1.4 \cdot 10^{6}$	$0.196 \cdot 10^{13}$	$3.77 \cdot 10^{-10}$	$2.762 \cdot 10^{-3}$
WB89-437	2.88	15	$3.820 \cdot 10^{-2}$	$3.3 \cdot 10^{6}$	$0.567 \cdot 10^{13}$	$3.99 \cdot 10^{-10}$	$3.443 \cdot 10^{-3}$
WB89-501	1.92	10	$1.760 \cdot 10^{-2}$	$1.0 \cdot 10^{5}$	$0.953 \cdot 10^{12}$	$8.51 \cdot 10^{-11}$	$3.619 \cdot 10^{-3}$
WB89-621	1.92	15	$1.004 \cdot 10^{-1}$	$3.6 \cdot 10^{6}$	$1.010 \cdot 10^{13}$	$7.77 \cdot 10^{-10}$	$9.064 \cdot 10^{-3}$
WB89-640	2.88	15	$8.004 \cdot 10^{-2}$	$3.2 \cdot 10^{5}$	$7.775 \cdot 10^{12}$	$2.43 \cdot 10^{-9}$	$7.366 \cdot 10^{-3}$
WB89-670	1.44	10	$7.059 \cdot 10^{-2}$	$5.5 \cdot 10^{5}$	$3.350 \cdot 10^{12}$	$4.59 \cdot 10^{-10}$	$1.148 \cdot 10^{-2}$
WB89-705	0.96	10	$9.289 \cdot 10^{-2}$	$1.0 \cdot 10^{5}$	$2.535 \cdot 10^{12}$	$1.49 \cdot 10^{-9}$	$1.922 \cdot 10^{-2}$
WB89-793	1.44	15	$7.057 \cdot 10^{-2}$	$4.5 \cdot 10^{5}$	$3.652 \cdot 10^{12}$	$6.19 \cdot 10^{-10}$	$6.424 \cdot 10^{-3}$
WB89-898	2.40	10	$2.710 \cdot 10^{-2}$	$1.0 \cdot 10^{5}$	$1.836 \cdot 10^{12}$	$7.34 \cdot 10^{-10}$	$5.577 \cdot 10^{-3}$
WB89-910	1.92	15	$4.001 \cdot 10^{-2}$	$6.6 \cdot 10^{6}$	$4.358 \cdot 10^{12}$	$1.32 \cdot 10^{-9}$	$3.586 \cdot 10^{-3}$

Table 3: CH_3OH-E Column Densities in Cold Molecular Clouds calculated via RADEX. *Excitation condition held constant: background temperature = 2.73 K.* This table lists column densities of 2_-1 – 1_-1 methanol in the examined sources of this survey project. Column one lists source name. Column two gives the source’s line width (Full-width at Half Maximum). Column three lists the kinetic temperature of the medium. Column four gives the radiation temperature. Column five gives the number density of collision partners. Column six gives the column density of each source to calculate the line strengths of methanol within each molecular cloud. Column seven provides the fractional abundances for each source. Column eight lists the tau of each source, which represents the optical depth at the center of the spectral line.

Table 4: $CH_3OH - E$ *Column Densities in Cold Molecular Clouds at 96.745 GHz*

Source	*ΔV* *(km· s^{-1})*	T_{ex} *(K)*	T_R *(K)*	H_2 *Density* *(cm^{-3})*	*N($CH_3OH - E$)* *(cm^{-2})*	*abundance*	tau
WB89-060	1.92	15	$2.145 \cdot 10^{-2}$	$1.1 \cdot 10^{6}$	$0.722 \cdot 10^{13}$	$7.76 \cdot 10^{-10}$	$2.014 \cdot 10^{-3}$
WB89-391	1.44	15	$1.018 \cdot 10^{-2}$	$1.4 \cdot 10^{6}$	$0.196 \cdot 10^{13}$	$3.77 \cdot 10^{-10}$	$9.256 \cdot 10^{-4}$
WB89-437	2.88	15	$1.659 \cdot 10^{-2}$	$3.3 \cdot 10^{6}$	$0.567 \cdot 10^{13}$	$3.99 \cdot 10^{-10}$	$1.415 \cdot 10^{-3}$
WB89-621	1.44	15	$4.446 \cdot 10^{-2}$	$3.6 \cdot 10^{6}$	$1.010 \cdot 10^{13}$	$7.77 \cdot 10^{-10}$	$3.803 \cdot 10^{-3}$
WB89-640	1.92	15	$2.878 \cdot 10^{-3}$	$3.2 \cdot 10^{5}$	$7.775 \cdot 10^{12}$	$2.43 \cdot 10^{-9}$	$5.352 \cdot 10^{-4}$
WB89-793	1.44	15	$1.428 \cdot 10^{-2}$	$4.5 \cdot 10^{5}$	$3.652 \cdot 10^{12}$	$6.19 \cdot 10^{-10}$	$1 .651 \cdot 10^{-3}$
WB89-910	1.44	15	$2.012 \cdot 10^{-2}$	$6.6 \cdot 10^{6}$	$4.358 \cdot 10^{12}$	$1.32 \cdot 10^{-9}$	$1.683 \cdot 10^{-3}$

Table 4: CH_3OH-E Column Densities in Cold Molecular Clouds calculated via RADEX. *Excitation condition held constant: background temperature = 2.73 K.* This table lists column densities of 2_0 – 1_0 methanol in the examined sources of this survey project. Column one lists source name. Column two gives the source's line width (Full-width at Half Maximum). Column three lists the kinetic temperature of the medium. Column four gives the radiation temperature. Column five gives the number density of collision partners. Column six gives the column density of each source to calculate the line strengths of methanol within each molecular cloud. Column seven provides the fractional abundances for each source. Column eight lists the tau of each source, which represents the optical depth at the center of the spectral line.

This initial study of CH_3OH in the far outer galaxy has revealed that methanol is a molecule that can readily be observed in the outer galaxy, even past distances of R_G > 16 kpc. In this survey project, we were able to observe methanol in two different conformations (CH_3OH-E + CH_3OH-A) and three different transitions (*2_0* → *1_0*, *2_-1* → *1_-1*, *2_0* → *1_0*). With our 96.7 GHz observations and H_2CO data provided in Blair's formaldehyde paper, we were able to determine CH_3OH column densities and abundances using simplified assumptions for the excitation temperature and H_2 Density. As in Blair's paper, we assumed that the line was optically thin. The results of CH_3OH-A with transition 2_0 → 1_0 is shown in Table 2, the results of CH_3OH-E with transition 2_-1→ 1_-1 is shown in Table 3, and the results of CH_3OH-E with a transition of 2_0 → 1_0 is shown in table 4. Abundances are further explained in the discussion section.

Discussion:

In 1995, Brand and Wouterloot asserted that GMCs in the inner galaxy are denser than those in the outer galaxy (Brand and Wouterloot (1995)). In several surveys of molecules such as nitrogen, oxygen, and sulfur (e.g. Rudolph et al. (2006)), Brand and Wouterloot's assertion has remained supported as these molecular species show significantly lower abundances and densities in far out molecular clouds than inner clouds. Methanol, being a molecule that exists in both ambient and star forming regions, has been observed in several locations throughout the galaxy. In dense interstellar clouds, methanol's fractional abundance relative to H_2 in cold extended portions of GMCs is confined to the range $3\cdot 10^{-9}$ to the order of 10^{-10} (Kalenskii and Sobolev (1993)). In hot star-forming regions such as the Compact Ridge and Hot Core sources of the Orion-KL nebula, the abundances increase to values ranging between $1\cdot 10^{-7}$- $1\cdot 10^{-6}$. The Orion molecular cloud is only on the order of 450 pc from earth, making its R_G substantially smaller than any of those studied during our survey. As such, the Orion molecular cloud and others like it may be used as representatives to compare CH_3OH abundance results from the outer galaxy to that of the inner galaxy.

In order to determine the fractional abundances of methanol in our observed molecular clouds, we used the simplified formula of:

$$\mathrm{CH_3OH\ fractional\ abundance} = \frac{N(CH_3OH)}{N(H_2)}$$

In this equation, $N(CH_3OH)$ is the column density of methanol used to calculate line strengths, and $N(H_2)$ is the hydrogen column density reported from the Blair formaldehyde survey. Using this equation, we are able to compare outer galaxy methanol cloud abundances to warmer inner galaxy methanol abundances. Determining whether the abundance of methanol with respect to hydrogen in the outer galaxy is less than the abundance in the inner galaxy is an important part of this survey project.

In 1994, Kalenskii and Sobolev condensed methanol abundance survey results of over 100 molecular clouds into their paper. The conclusion of their molecular cloud survey found that methanol abundances in cold clouds does not average higher than $1 \cdot 10^{-10}$ - $3 \cdot 10^{-9}$. They also found that clouds with massive star forming regions, such as those found in the inner galaxy, have average abundances of $1 \cdot 10^{-8}$. Our current findings show that we have a smaller methanol column density than that of an average inner molecular cloud such as the Orion-KL molecular cloud (Orion's methanol density shown in Table 5.). This remains consistent with Brand and Wouterloot's assertion. Furthermore, our findings also indicate that the abundances of methanol in the molecular clouds of our survey are similar to that which would be expected in colder clouds. This conclusion is favorable, but we must remember that several simplifying assumptions were used to determine our methanol abundances. As such, a more reliable determination of abundances for outer galactic methanol will come after completing more surveys of far molecular clouds to improve sample size, conducting multi-transitional studies to gain a more reliable picture of methanol in far regions of the galaxy, and comparing line intensities with Large-velocity gradient codes for increased accuracy. These are all steps that we have begun to take.

Table 5: CH_3OH *column densities in Orion-KL nebula*

	Component	Assumed source Size (")	$N(CH_3OH)$ (cm^{-2})
$^{12}CH_3OH$			
Optically thick			
	Narrow	25	$8.4\ (0.8) \cdot 10^{16}$
	Broad	15	$3.0\ (0.3) \cdot 10^{17}$
	Broad	25	$1.5\ (0.2) \cdot 10^{17}$
Optically thin			
	Narrow	25	$1.2\ (0.2) \cdot 10^{17}$
	Broad	15	$4.7\ (0.3) \cdot 10^{17}$
	Broad	25	$2.2\ (0.3) \cdot 10^{17}$
	Narrow	30	$1.0\ (0.2) \cdot 10^{17}$
	Broad	30	$1.7\ (0.2) \cdot 10^{17}$

Table 5: CH_3OH Column Densities in Hot Molecular Cloud of Orion-KL Nebula. *From K.M. Menten et al. study of Methanol in the Orion Region (Menten et al. (1987)).*

Given the initial success of this project, we will continue to seek out methanol in other far out GMCs. Going forward, we will also calculate the abundances of methanol in these molecular clouds in order to establish a quantity that can later be compared to other prebiotic abundances in the inner galaxy. The detection of methanol at our galaxy's molecular edge is a noteworthy result that can be utilized to address whether or not the abundances of methanol significantly decrease as distances from the galactic center increase. Upon analysis, findings may either support Brand and Wouterloot's claim or present a unique anomaly. Another future goal of this project is to begin looking for other prebiotic molecules that may be present at the edges of our galaxy. Possible candidate molecules include formamide ($HCON_2$), methyl formate ($HCOOCH_3$), and dimethyl ether (CH_3OCH_3), which like methanol, may undergo reactions producing building blocks of life such as sugars and amino acids.

To the best of our knowledge, this has been the first to attempt to find methanol distributions in the outer regions of the Milky Way. This pilot survey has revealed that methanol is a readily observable molecule even in molecular clouds with an R_G > 16 kpc. Observing methanol at 96.7 GHZ in roughly 82% of our surveyed clouds with R_G > 13 kpc indicates that methanol is may be a relatively abundant molecule in outer regions of our galaxy. Out of the 17 clouds that were a part of this survey, 9 were located in the far outer galaxy and had methanol detection rates nearly identical to that of the overall survey. This initial work suggests that the Galactic Habitable Zone, using prebiotic molecules as a constraint, may expand well past 9 kpc. Our findings align similarly to that of Blair et al. and her studies on prebiotic formaldehyde in the outer regions of the galaxy, and as more researchers continue conduct surveys on other prebiotic molecules and their abundances in distant regions of our galaxy, we may find that our Milky Way is capable of supporting the development of life in a zone far wider than ever anticipated before.

Abbreviations:

R_o= Distance of Sun from galactic center

R_G = Galactocentric distance

ISM = Interstellar medium

GHZ = Galactic Habitable Zone

GMCs = Giant Molecular Clouds

IRAS = Infrared Astronomical Satellite

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